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13. ABSTRACT *(Maximum 200 words)*
The objectives of this work were to develop devices for optical interconnects in the mid-IR, develop devices for mid-IR ranging, IR decoy projection, free space communication, pollution monitoring, and digital optical logic. In addition, it was desired to three dimensional opto-electronic systems with very large scale integrated optics with ultra high confinement waveguides. Advances included the use of quantum wells in the electrode to reduce free electron absorption; use of electrode resonances in the far-IR to reduce penetration of mid-IR light; and use of step wells and dope in barrier to lower linewidth and increase separation of states.

14. SUBJECT TERMS mid-IR modulators, ultra high confinement integrated optics, fast opto-electronic quantum well amplitude modulator

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Fast Opto-Electronic Quantum Well Amplitude Modulator

ARPA Contract DAAL03-90-C-0019

Final Report
May 10, 1995

Version 0.0

Submitted by

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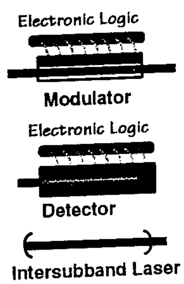
Objectives

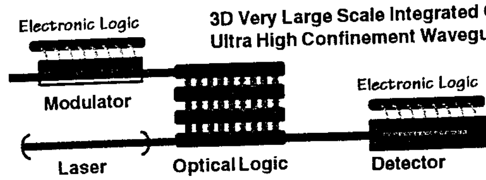
Devices:



- Optical Interconnects in mid-IR
  - Less Watts per Quanta Flux
    - > *Lower IR Powers*
- Mid-IR Ranging
- IR Decoy Projection
- Free Space Communications
- Pollution Monitoring
- Digital Optical Logic

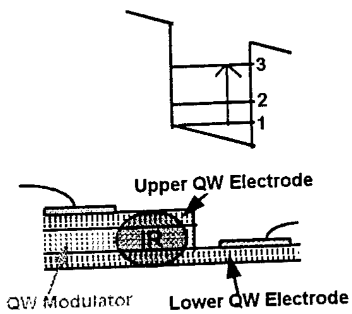
Opto-Electronic Systems:

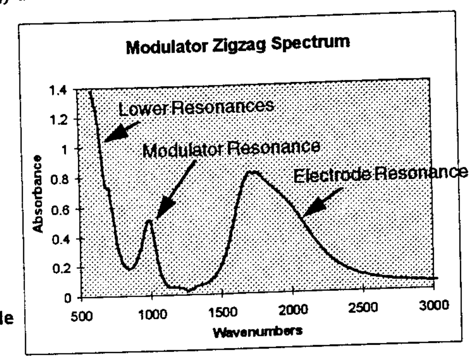
3D Very Large Scale Integrated Optics *with* Ultra High Confinement Waveguides



Modulator Physics

- **1->3 Transition has been isolated from free carrier, and lower level transition absorption.**
  - Lower level transitions are narrowed by doping in barriers.
  - Lower level transitions are positioned for minimum loss.
- **Free carrier loss has been minimized, while maintaining good electrical properties, using QWs as electrodes**
  - Eliminated field exclusion at modulation wavelength by placing the QW electrode resonance at a higher energy than the modulator resonance so it's index is positive.

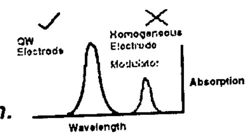




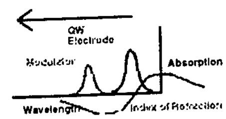
Lessons Learned From Bulk Modulator

- Problem - *Solution*

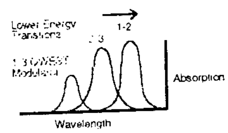
- Free electron absorption is strong in highly doped electrode regions. - *Use QWs in electrode to reduce free electron absorption.*



- Electrode resonance in far-IR reduces penetration of mid-IR light (lowers refractive index) - *Resonance must be higher energy than modulator resonance.*



- Lower level transitions can cause residual absorption - *Use step wells and dope in barrier to lower linewidth and increase separation of these states.*

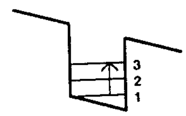


Electronic Logic

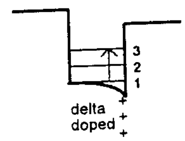
Modulator

Intersubband Modulation

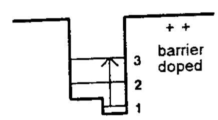
- **Modulator Mechanism**
  - Break symmetry with electric fields to allow 1-3 transition.



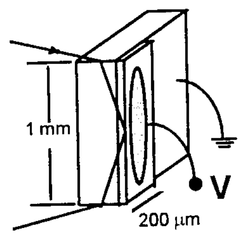
- **A built-in field is created with delta doping on edge of well.**
  - Allows observation in spectrometer without application of field.



- **Doping outside well allows narrower, stronger lines with less interference from other lines.**
  - Use step in Al concentration to create built-in field.

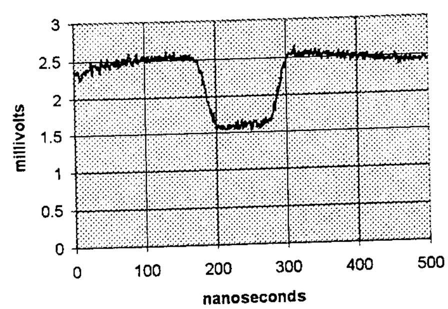


Bulk Modulator

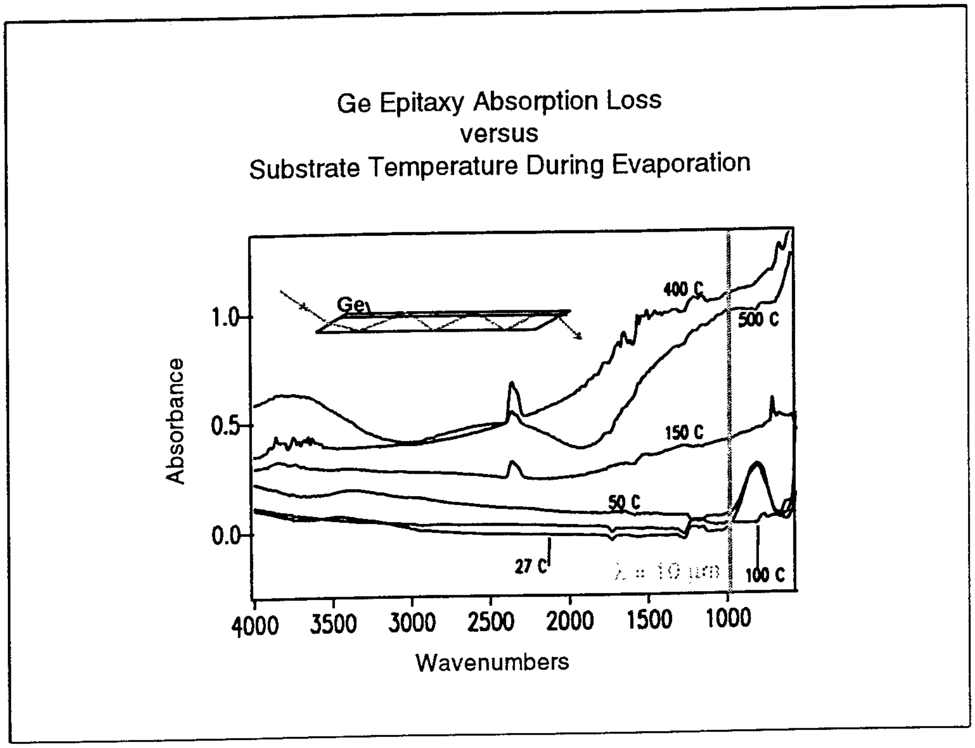


R = 35 Ohm
C = 11 pF

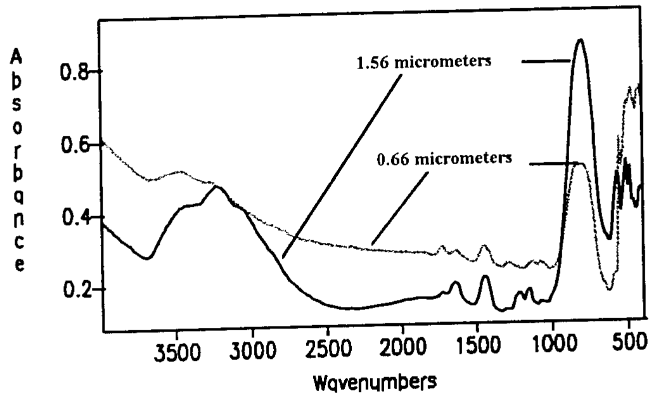
RC = 400 psec



Demonstrated Risetime << 10 nsecs
(limited by Function Generator and Detector)
A 20 volt, 100 nsec wide electrical pulse was applied.


Ge Epitaxy Absorption Loss
versus
Substrate Temperature During Evaporation
Ge
400 C
500 C
150 C
50 C
27 C
100 C
λ = 10 μm
1.0
0.5
0.0
Absorbance
4000
3500
3000
2500
2000
1500
1000
Wavenumbers

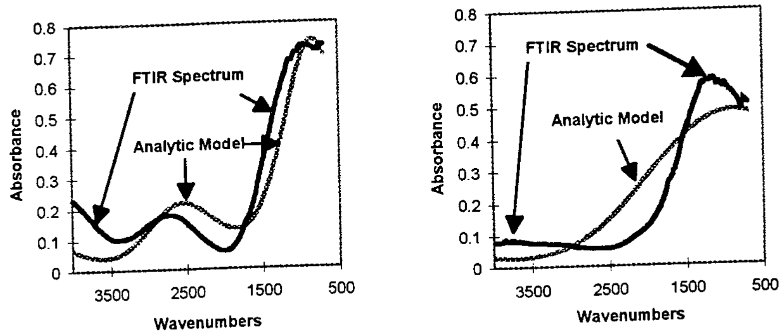
Low Temperature Ge Growth



The absorption peak at 830 cm^{-1} decreases in proportion to the thickness of the sample when etched, indicating a bulk effect. This is now believed to be from incorporation of Ge Oxide.

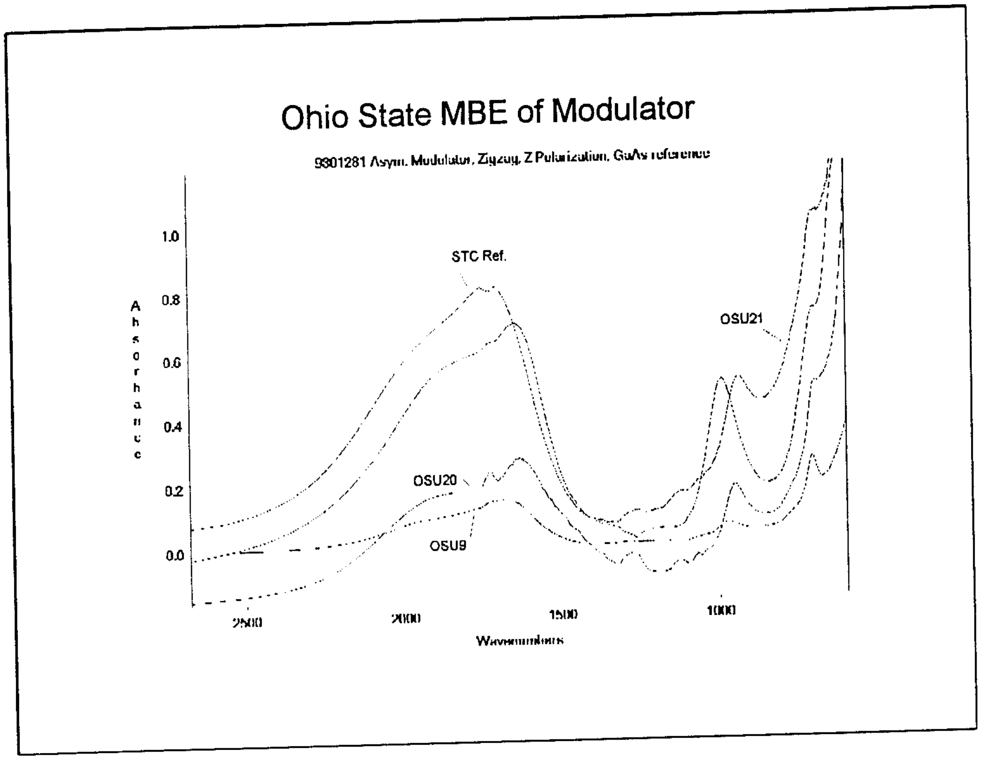
The absorption peak at 830 cm-1 for the films grown at RT and 50 °C decreases in proportion to a 68% decrease in Ge film thickness via a chemical etch, indicating the features are from a bulk effect. The broad peak at 3200 cm-1 has a similar behavior. This spectrum was also found to be polarization independent.

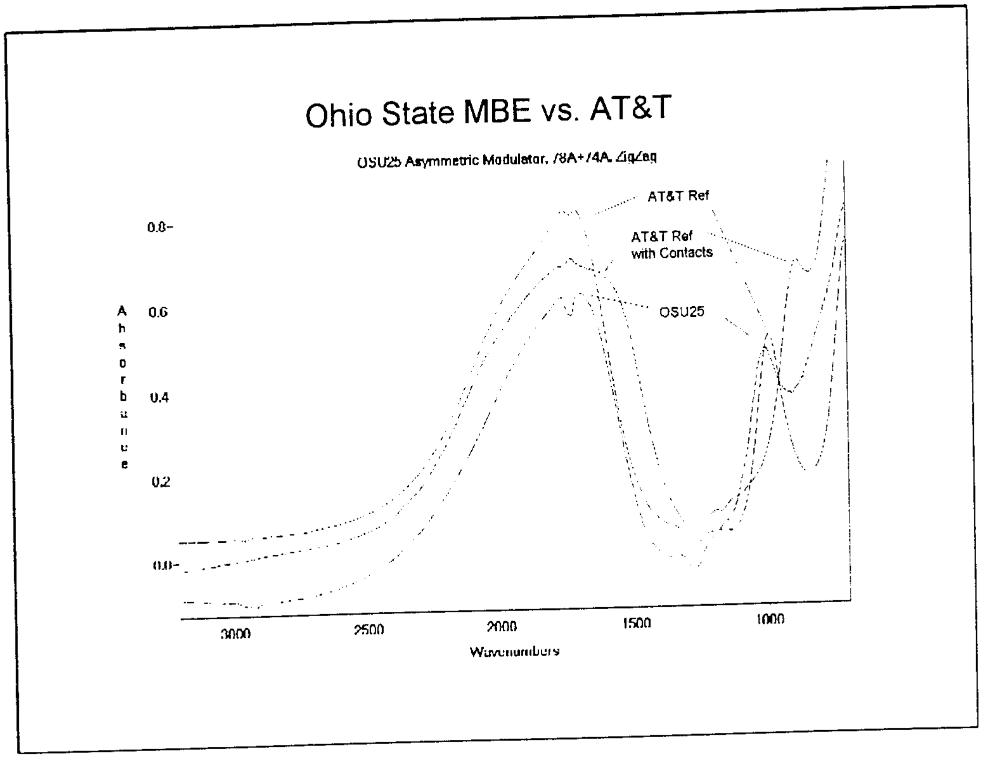
High Temperature Ge Growth



As the high temperature sample is etched, the magnitude of the absorption stays constant, but the oscillation frequency changes. This is expected from a thin polarized absorber at the Ge/GaAs interface, likely to be free electrons from interdiffusion.

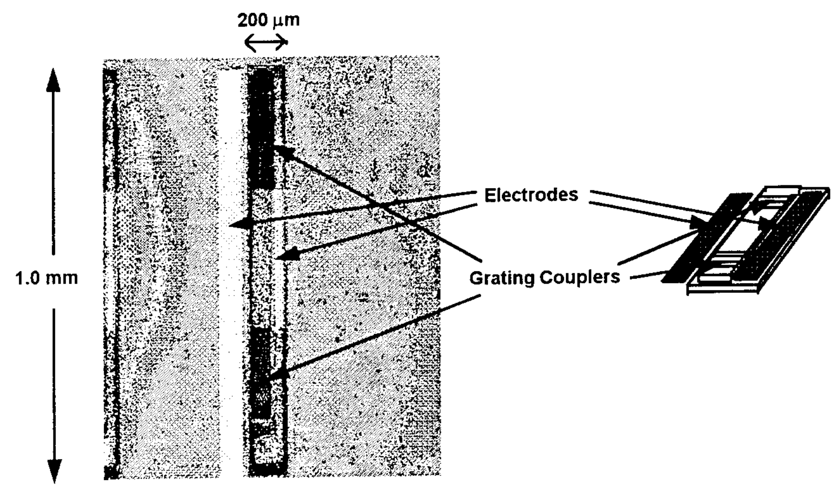
Figure 3. The absorption spectra for the UHV Ge film deposited at 500 C before, (a), and after, (b), removal of 54% of the Ge film from 1.15 mm to 0.53 mm. using a chemical etch. The much-less-than-linear thickness dependence in the magnitude of the Absorbance indicates this absorption is from an interface. The oscillations in wavelength are expected for a polarization dependent thin film absorber because of interference of the total internally reflected beams. Fig. 3(a) shows the measured and analytic multilayer interference model for a thin birefringent layer at the Ge/GaAs interface. The absorption is taken to be birefringent with a Drude model laterally and an intersubband in the confinement direction. The analytic model required a Ge thickness of 0.97 mm to position the spectral peaks and valleys at the wavenumbers as shown whereas the actual thickness was measured to be 1.15 mm. The analytic curve in Fig. 3(b) uses the same model parameters as for 3(a), but with a Ge thickness of 0.47 mm, close to the measured 0.53 mm thickness of Ge film obtained after chemical etching. Note the observed change in spectral behavior is also qualitatively similar to that expected for a thin birefringent absorber at the Ge/GaAs interface.


Ohio State MBE of Modulator
9301281 Asym. Modulator, Zigzag, Z Polarization, GaAs reference
Absorbance
1.0
0.8
0.6
0.4
0.2
0.0
STC Ref.
OSU21
OSU20
OSU9
2500
2000
1500
1000
Wavenumbers

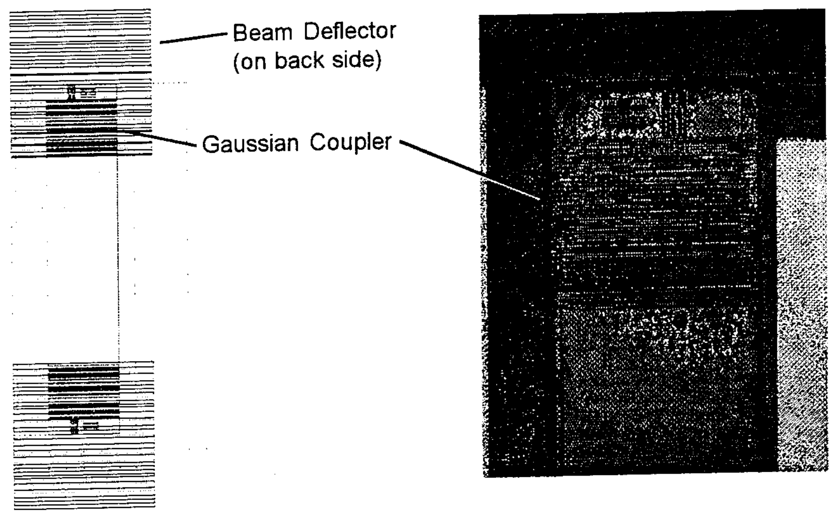


Ohio State MBE vs. AT&T
OSU25 Asymmetric Modulator, 78A+74A, ∆q∆eq
AT&T Ref
AT&T Ref
with Contacts
OSU25
Absorbance
0.8
0.6
0.4
0.2
0.0
3000
2500
2000
1500
1000
Wavenumbers

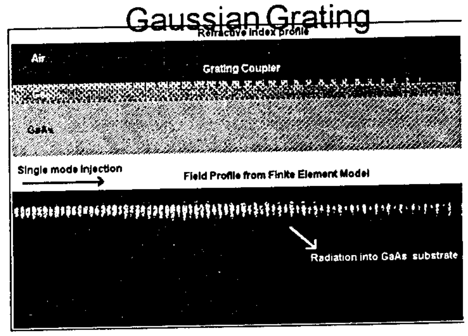
Slab Waveguide Modulator

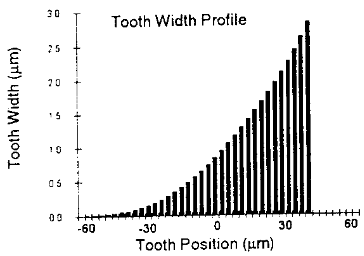


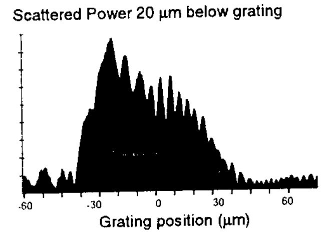
Slab Modulator with Gaussian Coupler

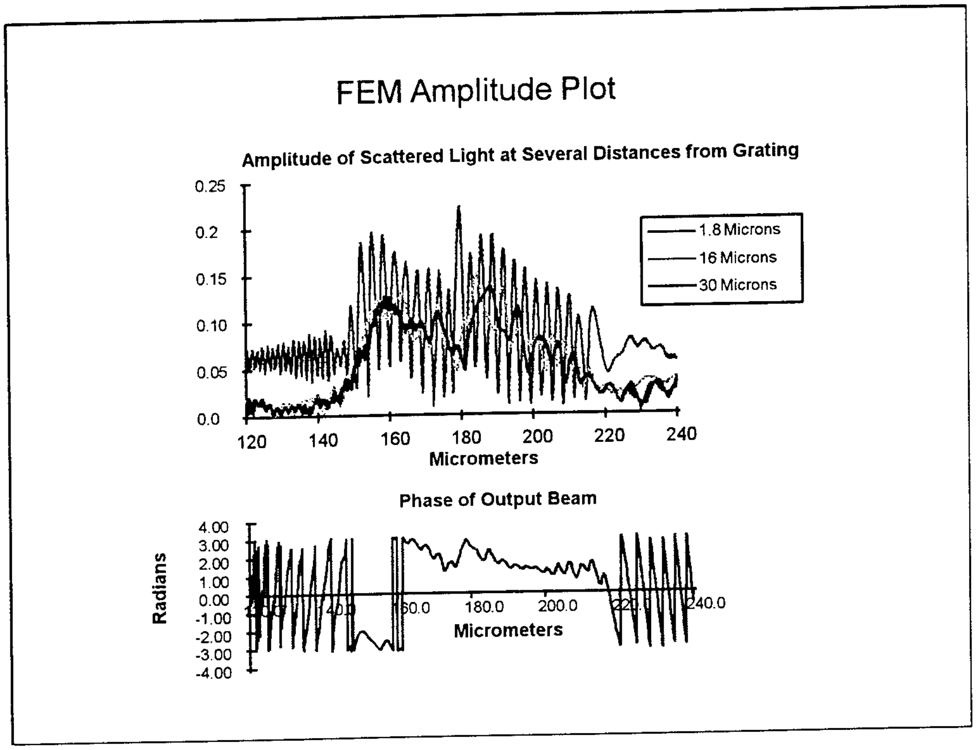


Gaussian Grating



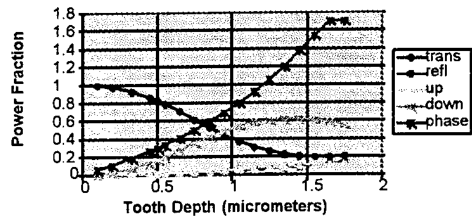


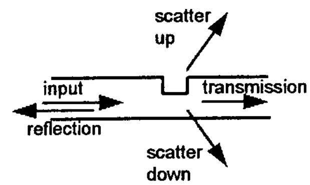



FEM Amplitude Plot
Amplitude of Scattered Light at Several Distances from Grating
0.25
0.2
0.15
0.10
0.05
0.0
120
140
160
180
200
220
240
Micrometers
1.8 Microns
16 Microns
30 Microns
Phase of Output Beam
Radians
4.00
3.00
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
180.0
200.0
240.0
Micrometers

Coupling per Tooth

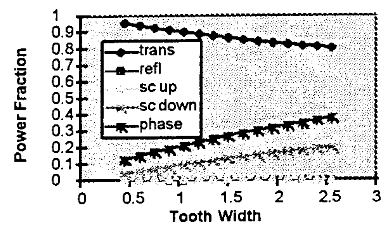
Tooth Width = 1.5 microns



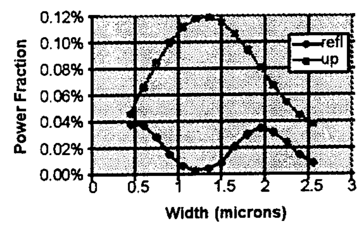


Note tooth reflection has a minimum around 1.2 microns.

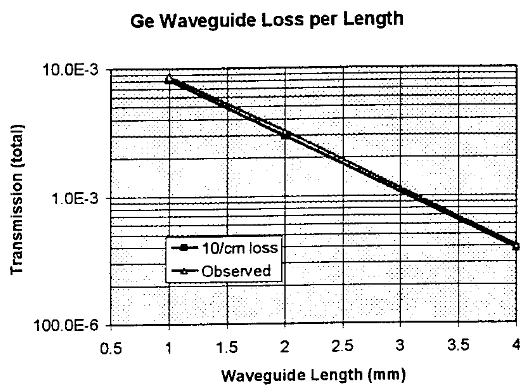
Tooth Depth = 0.45 microns



Tooth Depth = 0.2 micron



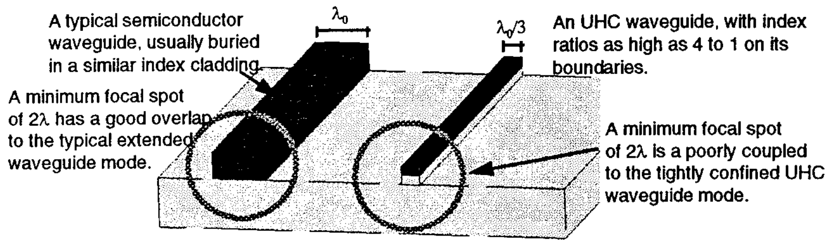
Slab Waveguide Performance

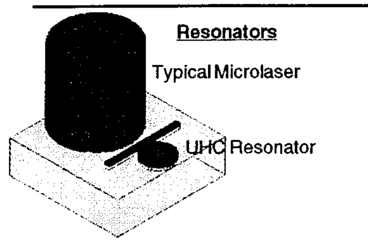


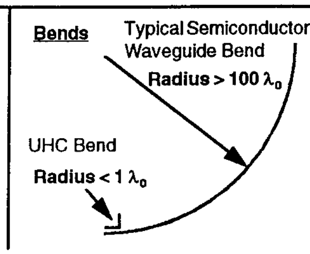
Efficiency	Expected	Observe
Delta n (Fresnel)	0.8	0.8
Beam Deflector	0.65	0.35
Gaussian Grating	0.55	0.54
Single Couple	0.286	0.152
Double Couple	**0.082**	**0.023**

Ultra High Confinement Integrated Optics

- **Dramatically improved opto-electronic device performance.**
- **Very Large Scale Integrated Optics (VLSIO)**



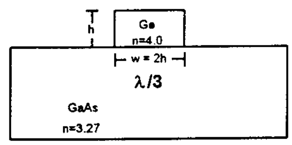




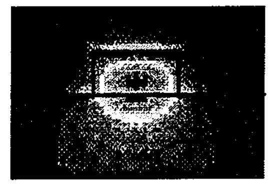
Ultra High Confinement Waveguides

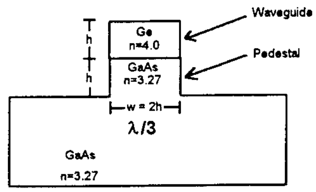
Cross Sectional Area < 0.1 λ^2

Vertical component of electric fields. (from Finite Element Modeling)

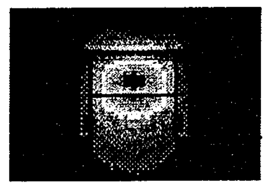


Rectangular Waveguide

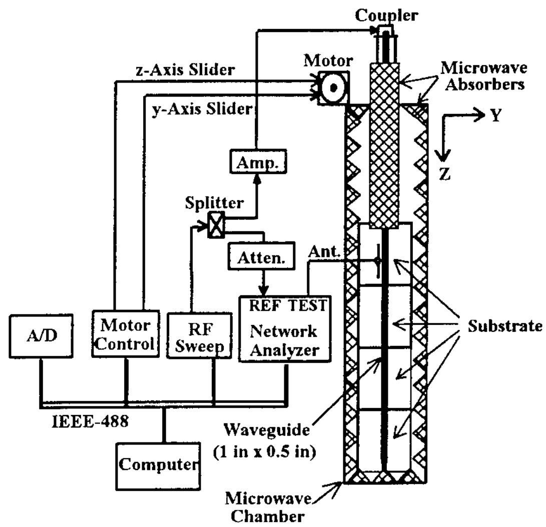


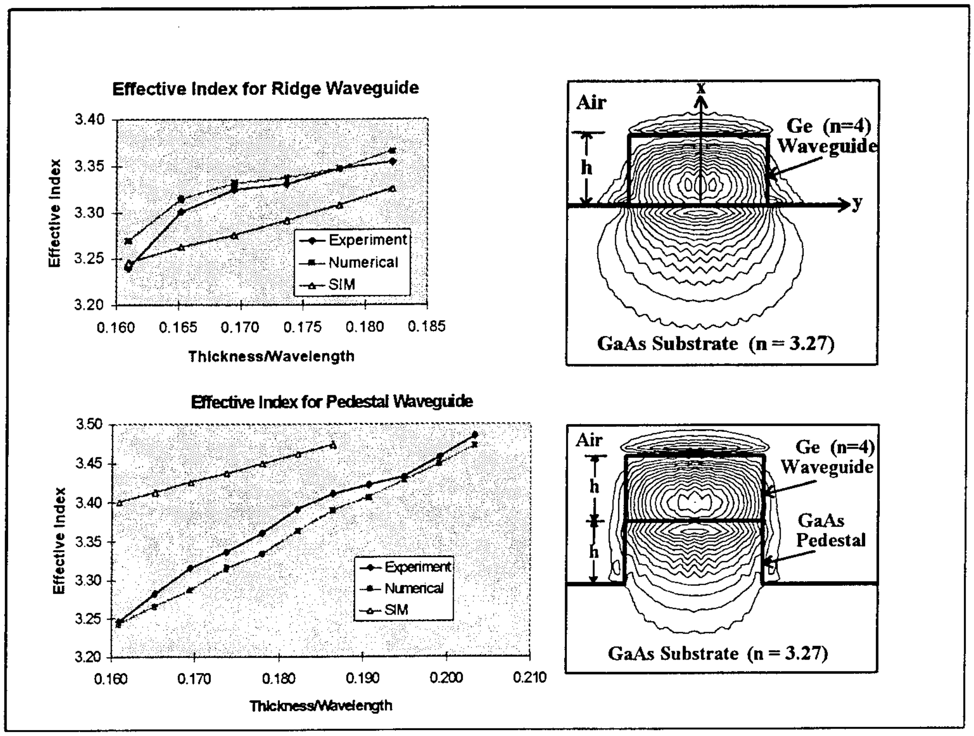


Pedestal Waveguide

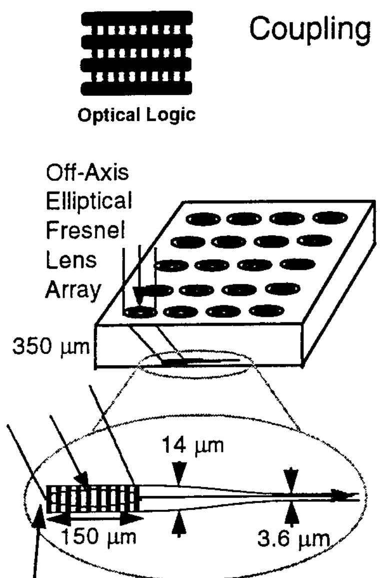


Microwave Scale Waveguide Experiments

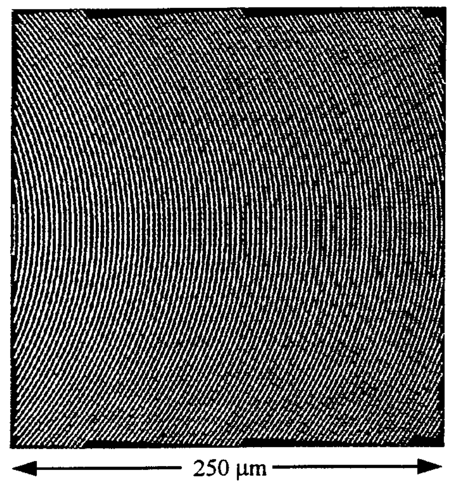



Effective Index for Ridge Waveguide
Effective Index
3.40
3.35
3.30
3.25
3.20
0.160
0.165
0.170
0.175
0.180
0.185
Thickness/Wavelength
Experiment
Numerical
SIM
Air
x
y
h
Ge (n=4)
Waveguide
GaAs Substrate (n = 3.27)
Effective Index for Pedestal Waveguide
Effective Index
3.50
3.45
3.40
3.35
3.30
3.25
3.20
0.160
0.170
0.180
0.190
0.200
0.210
Thickness/Wavelength
Experiment
Numerical
SIM
Air
h
h
Ge (n=4)
Waveguide
GaAs
Pedestal
GaAs Substrate (n = 3.27)

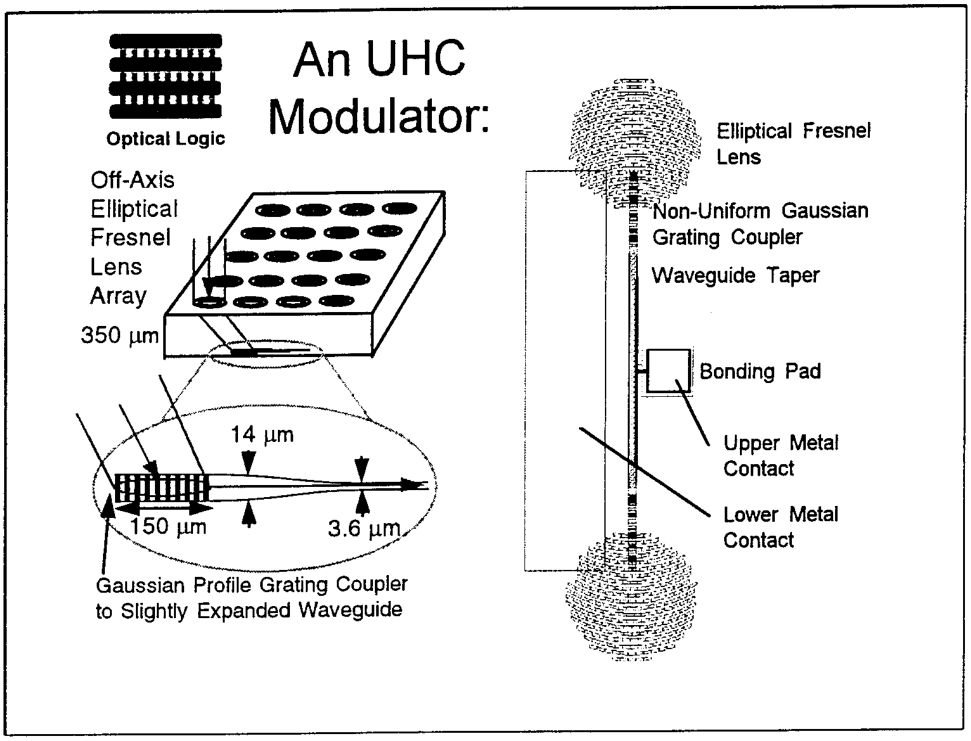
Coupling into Waveguides



Gaussian Profile Grating Coupler
to Slightly Expanded Waveguide



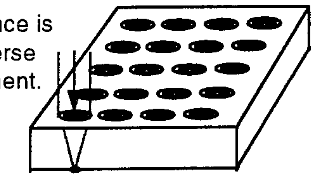
Off-Axis Elliptical Fresnel Lens

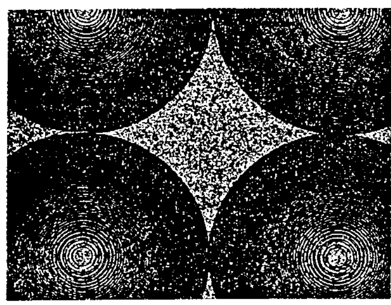


An UHC Modulator:
Optical Logic
Off-Axis Elliptical Fresnel Lens Array
350 μm
14 μm
150 μm
3.6 μm
Gaussian Profile Grating Coupler to Slightly Expanded Waveguide
Elliptical Fresnel Lens
Non-Uniform Gaussian Grating Coupler
Waveguide Taper
Bonding Pad
Upper Metal Contact
Lower Metal Contact

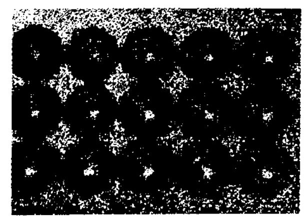
Through-Wafer Alignment

CO_2 laser beam at normal incidence is used to create burn spots on reverse side of wafer for back-side alignment.





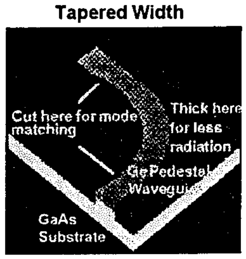
Fresnel Lenses



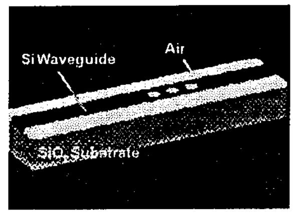
Focusing
Near-IR
White Light

Bends and Resonators

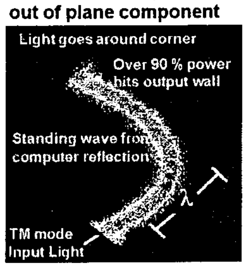
Tapered Width



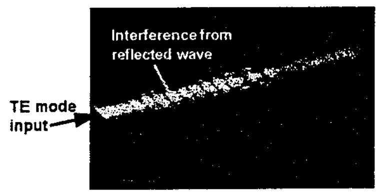
Si on SiO_2 Resonator



Electric field amplitude for out of plane component

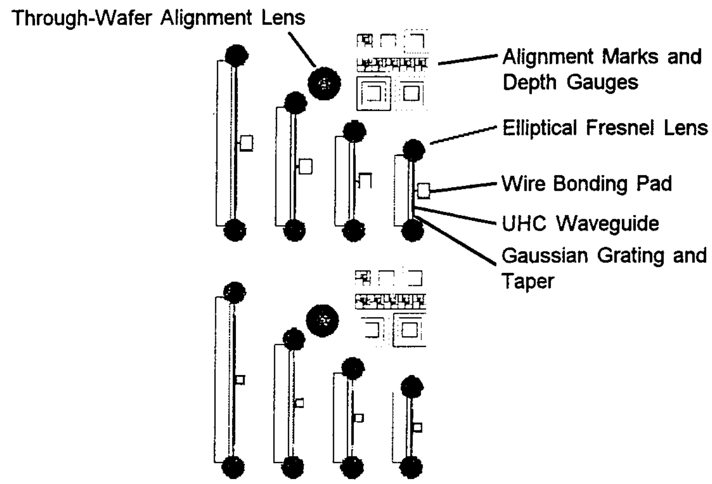


TE Mode Reflection

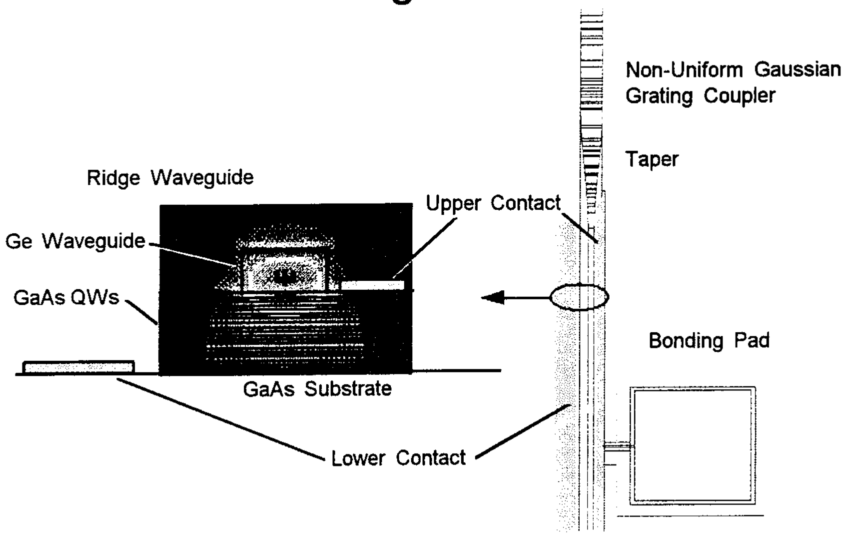


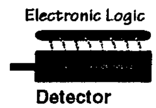
Low loss reflection indicates a cavity with a Q > 100 is possible

UHC Waveguide Modulator



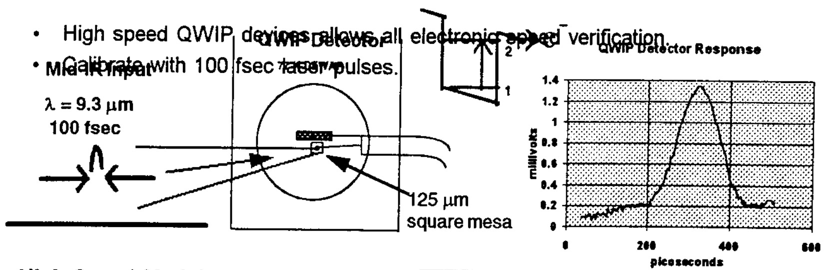
Active UHC Waveguide





Detector Physics and System Test

- High speed QWIP devices allows all electronic speed verification.
- Calibrate with 100 fsec laser pulses.



High Speed Modulator Evaluation: